Understanding the relationship between design margins and trade-offs

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UNDERSTANDING THE RELATIONSHIP BETWEEN DESIGN MARGINS AND TRADE-OFFS

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1. Introduction

Manufacturing companies are facing pressure to increase product performance while simultaneously reducing cost. They have responded to this need by considering different optimisation strategies and sharing common components among different platforms. However, the optimisation of an individual product can conflict with the use of the same components across a product platform [Isaksson et al. 2014]. During the early product development phases, decisions are made about which architectures and configurations are better than others. Later when the key configuration and design choices have been made, the obligation is to determine the optimal values for all the detailed design parameters with regards to the overall product platform and its future development. This paper will argue that this can be seen as a decision about the margins on design parameters compared to the optimal value. Margins can be seen as a way of measuring how "sub-optimal" a product is and whether the cost is acceptable. This enables companies to make decisions about how many options they want to include in the product platform.

To understand this in more detail we need to unpack the concept of margin in more detail. Margins are included for different reasons in the course of a product design process and have two elements. One element that protects the design from changes arising from uncertainties in design or use and the other that can be considered as genuine overdesign. In Isaksson et al. [2014] we developed the idea of a trade-of between an optimal design and an optimal platform using the margin on a single parameter as an example. In this paper we extend this to margins on multiple parameters that are traded-off against each other. This will be illustrated through the example of a truck cooling system.

2. Theoretical background

The research reported here addresses complex engineering products in the automotive and aerospace industry. The products in these industry sectors are mainly based on platforms, so components, systems and features are shared across a range of products. Yet, these types of products can also be subject to wide variations depending on customer requirements. Therefore companies offer product platforms with options. The aim is to cover the entire design space. To manage the computational complexity of the product platform, design engineers are constantly trying to make trade-offs to balance the optimisation of an individual product and the maximisation of standard components across a product platform [De Weck et al. 2000]. The challenge for companies is to develop an optimal platform that enables them to meet the needs of their customers with minimal cost and design effort.

As Otto and Antonsson [1991] point out an optimal system design is not necessarily the one which optimizes specific features individually, but one which maximizes the overall performance of a design.

These overall performance features of a design are prescribed by key parameters such as operating conditions, geometry, and power output, for example, which are the subject of a series of trade-off decisions over the course of the design process. A significant aspect in trade-offs is the adaptability of a product to the particular requirements of a product variant. Adaptability is defined as the ability of the system to meet a wide range of functional requirements without requiring physical modification [Gu et al. 2009] even if these are not known when the product is originally designed. A design aims at finding a solution that satisfies several different functional requirements. A designer aims at finding a solution that satisfies several different functional requirements. To make a design resilient to change and easily adaptable if a change is necessary, designers consider dependencies between the different requirements. Adaptability can arise from design margins on components or systems, which exceed the initial requirements. This is considered in the work on design options [de Neufville et al. 2006], which plans in a type of margin for anticipated design changes or upgrades at a later date. Similarly design for changeability [Frigge and Schulz 2005] and design for variability [Martin and Ishii 2002] also consider explicitly potential future changes. However, this can in practice be problematic as requirements emerge externally from customers, competitors and legislators and internally from business requirements and changes to other components. Rather than making the changes explicit, this research aims to make the margins explicit. This can enable designers to accommodate the changes.
In this research, a margin is defined as "the value a parameter has above and beyond what it needs to meet its functional requirements regardless of the motivation for which it was included" [Eckert et al. 2013]. Ross et al. [2008] developed a method for comparison of the possible design options by mapping out a tradespace for potential solutions. This tradespace describes the range of possible values on component and system parameters, as well as on key parameters of the overall product, that provide potential solutions. Design margins on parameters lie within the tradespace of possible values.

3. Methodology

This research was carried out as a part of an industrial project between the Open University, Volvo Trucks Technology and GKN Aerospace. At the beginning of the project 10 semi-structured interviews were conducted with engineers and designers from the truck company to understand how and when margins are added or deducted from the components and parameters; and how they were conceptualised. The interviewees were experienced designers, engineers and managers who work in different departments. All interviews were recorded, then transcribed and reviewed in order to highlight common themes. The results were played back to the company in a number of presentations. The study revealed that margins are added both to the requirements and the solutions created to respond to them. Different teams in the company add margins for different reasons and use different terminologies when referring to them, such as room for growth, overdesign, safety margins, as well as the business or technical motivations behind adding these margins. To trace the development of margins throughout the design process, it was decided to focus on one sub system in the truck, the cooling system, to gain an initial overview. This paper focusses on the margins that designers add beyond the requirements.
After developing a change prediction matrix (see [Keller et al. 2009]) to understand the dependencies in a cooling system, six follow-up interviews, again recorded and partially transcribed, were conducted with twelve engineers and designers from the cooling system team to understand how design changes affected the margins on components during the design process and to identify patterns in the mapping between changes and margins. The engine cooling fan was selected as a key component with high power consumption and has a highly space constrained geometry.

4. Margins and trade-offs

Design margins are introduced, used up or removed, across the development process from early conceptual design to later detailed design. Eckert et al. [2013] considered margins as consisting of two elements: a buffer, which allows for uncertainties (in product performance or customer requirements) and an excess, which can be used to meet possible new requirements. This view of margins relates to the concept of excess introduced by [Tackett et al. 2014], but admits explicitly that a product design is subject to uncertainties. The excess is the part of the margin that designers can use to respond to change. They can increase excess by reducing the uncertainty that the component or parameter is subject to.

For a performance parameter the margin is the difference between the actual and the required performance. To illustrate this with a simple example. A rectangle that has an area of 4 m^2 but only requires 1 m^2 has a margin of 3 m^2. If the requirement is increased, but is still < 4 m^2, no change is required, however it is greater than the area needs to be increased. As the area = lengths * width, either the lengths or the width or both can be changed. In practice one of the parameters might be a constraint, such as when the material is cut from a roll with a fixed width. In this case the length would be increased. If both are variable their might be other constraints or requirements that govern the ratio of both and the designers might need to made a trade-off between the lengths and width to find the best solution for this square. In the case of continuous variables it might be possible to find an optimum through carrying out a multi objective optimisation. This discrete variables trade-off might be compromised between weighted parameter. For example when selecting a chair a choice might exist between a red chair with armrests and a green chair without. Your favourite colour is green, and you prefer armrests. The choice depends on what is more important.

The margins on individual parameters provide a space in which trade-off for change can be made. As the example of area illustrates, some parameters might be harder to change than others. Figure 1 illustrates how the different trade-offs between two parameters $P_a$and P_b could be made. The designers might want again to build a margin into the new solution. The values of each of the two parameters include a margin. Thus $P_a min$ a minimum value for parameter P_a which is not an absolute minimum for that parameter but includes a margin to allow for upcoming uncertainties. $P_a max$ might give a maximum value for the parameter, for example size.

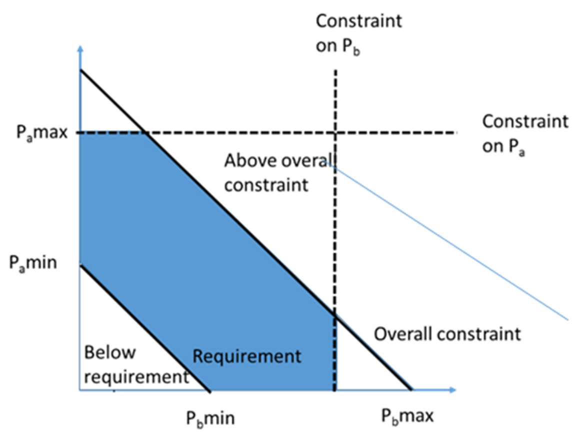

Figure 1. Trade-off between two parameters, P_a and P_b with regards to their margins

The parameter pair $\{P_a min, P_b min\}$ represents designs where the values for both parameters are at the minimum, that meets the requirements but has no margin. Solutions near or below these parameters are not considered desirable by designers. The parameter pairs $\{P_b min, P_a max\}$ and $\{P_b max, P_a min\}$ represent situations where parameters P_a and P_b are traded-off against each other and represent feasible design solutions. The pair $\{P_a max, P_b max\}$ represents situations where the values for both parameters are at their maximum. Design requirements are achieved and the solution is considered desirable. Therefore, the performance function F is maximised. However, if the objective is to optimize a performance function by minimizing some parameters, then $\{P_a min, P_b min\}$ would indicate the desirable design space and $\{P_a max, P_b max\}$ the undesirable one. The overall value might also be a constraint, for example when there is a weight limit on a rectangle with a given area.. In this case, the area above the solid line in Figure 1 would not yield a feasible solution. This approach of trading off parameters that have margins, offers designers and decision makers the possibility to explore different areas where the design could be feasible as well as judging the appropriate criteria for selecting a specific design solution. In Figure 1 the blue area represents the usable trade-off space.

In practice the relationship of the parameters is rarely linear as in Figure 1. For example a beam has a load capacity depending on its length and its diameter, which can be optimised through a Pareto optimisation. The actual solution is the red point, which is at a distance from the optimal solution.

Therefore there is a margin compared to the Pareto curve on the length and the diameter. The existence of these margins will help the designers make trade-offs between the length and diameter against each other and select the optimal solution that meets the requirement.

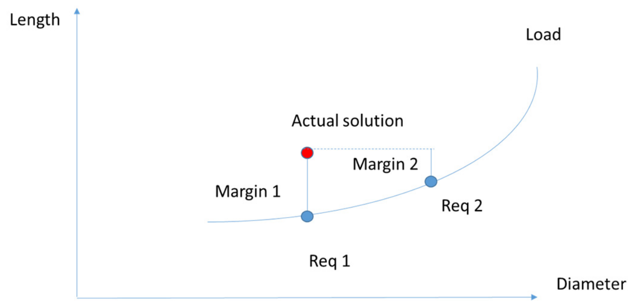

Figure 2. Margins on different parameters

In industrial applications the relationships are far more complex than in these simple examples. However designers are often aware of the margins and constraints they have on components; or can use analysis software to find out where margins might lie.

5. Application: A truck cooling system

5.1 Truck design

The relationship between margins and trade-offs is now illustrated through an industrial example of from our truck case study. Trucks are incremental designs. Every 10 to 15 years the company launches a new product generation, such as a new heavy weight truck, which see a substantial number of newly designed components and systems. In between these large product development cycles new versions are developed for particular classes of needs. For example after launching a basic version, the company later embarked in developing trucks that can be used as fire engines. The automotive industry also needs to meet different and changing emission legislations for different markets. The product generation changes are linked to the emission legislations, but engines are modified throughout the life cycle of a product generation. The automotive industry faces a number of technological challenges in terms of meeting different legislations, developing highly customised products to satisfy customer needs, and particular operating conditions. There are also challenges in terms of the lead time, and the trade-off between cost and the overall product development / performance. To illustrate this the cooling system of the truck was selected. The cooling system needs to be modified, but the engine temperature increases for whatever reason. This could either be a different engine, the truck could be operated in a different environment or on a different duty. In many driving conditions, the air flow crossing the radiator is not enough to cool the coolant. This happens for example in hot climates, or when the engine is running for a long time without moving the vehicle. When this is the case, the fan, located behind the radiator, is engaged and it helps pulling more air across the radiator. For example a truck operating in open mines in the desert requires substantially more cooling than a truck running on Eurorean motorways and would operate the fan most of the time. These challenges force companies to find an efficient way to make these trade-offs. Design margins are important for many trade-offs that engineers can make, as they represent a room for manoeuvre. Design margins can accommodate new requirements; therefore engineers can avoid redesigning their existing components and systems, which ultimately will result in decreasing the development time and cost.

5.2 The cooling system

For most use scenarios the heat that is produced in the engine needs to be actively cooled. This is performed by the cooling package which consists the radiator and the fan. When the engine coolant temperature rises to a threshold level, this will activate a valve, which will in turn send air pressure from the truck's air reservoir to the fan drive and engage the fan. When engaged, the fan drive activates the

fan to cool the engine by pulling air through the radiator. The amount of cooling provided is depending on the airflow generated by the fan.
At the same time the coolant system also can be used for heating; the heat transferred from the engine to the coolant is for example used in the cab heat exchanger in order to give the driver a comfortable temperature inside the cab. The cooling system (Figure 3) has tight geometrical constraints. It has the cab flooring on the top, on the sides of the chassis frame, the grille in the front, at the bottom the front underrun protection (FUP) and the engine in the back. To increase cooling the airflow needs to be increase.

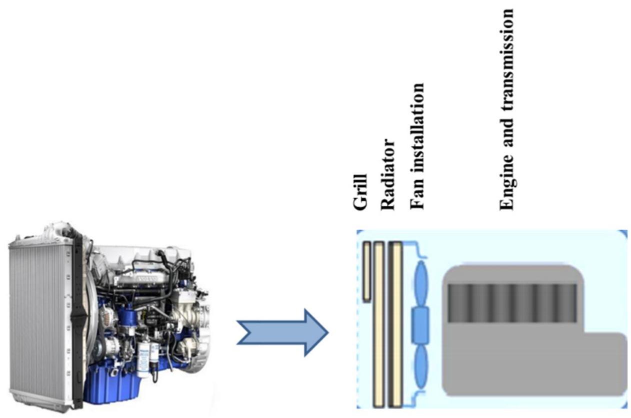

Figure 3. A cooling system layout

Different engine specifications have different cooling needs, according to the size of the engine and the load on it. The company offers a wide range of truck variations and configurations. Specific trucks are built from a product platform, which aims to meet the widest possible range of application with the minimal number of components and systems. This means that some components have large margins in performance with regards to the requirements of a particular configuration. The fan is one of these critical components that are shared across several configurations.

5.3 Margins on the cooling fan

Fans are usually selected from a range of models and sizes, rather than being designed specifically for a particular application. Fan selection is mainly based on calculating the airflow and pressure requirements of a system, then finding a fan of the right design to meet these requirements. Considering that they only use a small number of sizes of fan it is the rotational speed that is varied in practice.
As the company needs to be sure that they can meet the requirements under all the given scenarios they calculate the size of the fan and the fan speed they would like and use this as an input to select the right fan with a suitable fan speed.
The fan overall performance is determined by the fan capacity, pressure, speed and power, which follow the following fan laws [Gullberg and Sengupta 2011], which address the change required compared to an already existing baseline design which has been tried and tested for a given set of operating conditions.

$$q_2 = q_1 \times \left(\frac{n_2}{n_1}\right) \times \left(\frac{d_2}{d_1}\right)^3 \quad (1)$$

$$p_2 = p_1 \times \left(\frac{n_2}{n_1}\right)^2 \times \left(\frac{d_2}{d_1}\right)^2 \times \left(\frac{\rho_2}{\rho_1}\right) \quad (2)$$

$$P_{R2} = P_{R1} \times \left(\frac{n_2}{n_1}\right)^3 \times \left(\frac{d_2}{d_1}\right)^5 \times \left(\frac{\rho_2}{\rho_1}\right) \quad (3)$$

The Design parameters are: d for Diameter [m]; n for Rotational speed [rpm]; P_R for Power [rpmkW];

p for Pressure [Pa]; q_v for Volumetric flow rate [m^3 /s] and ρ for Density of air [kg/m^3]. Subscript 1 refers to the existing conditions and subscript 2 refers to the required conditions.

Higher airflow usually means better cooling. Consider a design requirement regarding the airflow that the cooling system must create for a particular engine and operating conditions. From the first fan law (1) we know that the airflow varies in direct proportion to the rotational speed. Therefore, the design requirement can be met by two design parameters which are the rotational speed of the fan and the fan diameter (size).

There are existing designs which meet these requirements, but since most of the fans are generally overdesigned, the solution exceeds the initial requirement for this particular design. For example an existing airflow of q_1 = 1.3CFM can be achieved with a fan diameter d_1 = 680mm, and a rotational speed n_1 = 1.06 RPM. Whereas, the needed air flow is only q_2 = 1CFM. In order to evaluate what is the actual needed fan diameter d_2 and the rotational speed n_2, we apply the first law (1):

$$q_2 = q_1 \times \frac{n_2}{n_1} \times (\frac{d_2}{d_1})^3 \quad (4)$$

Then,

$$d_2 = d_1 \times \sqrt[3]{\frac{q_2}{q_1} * \frac{n_1}{n_2}} \quad (5)$$

Figure 4 shows the variation of the fan diameter with the rotational speed. The Pareto curve obtained for this installation shows that at the fan speed ratio 1.06 RPM, the fan diameter would be 623.057mm. On the other hand, for a fan diameter of 680mm the fan speed ratio is 0.80 RPM. But in reality the installation is using a fan that operates at a diameter of 680mm at a speed ratio of 1.06RPM. Therefore there is a margin on *d* the diameter of the fan and a margin on *n* the rotational speed of the fan.

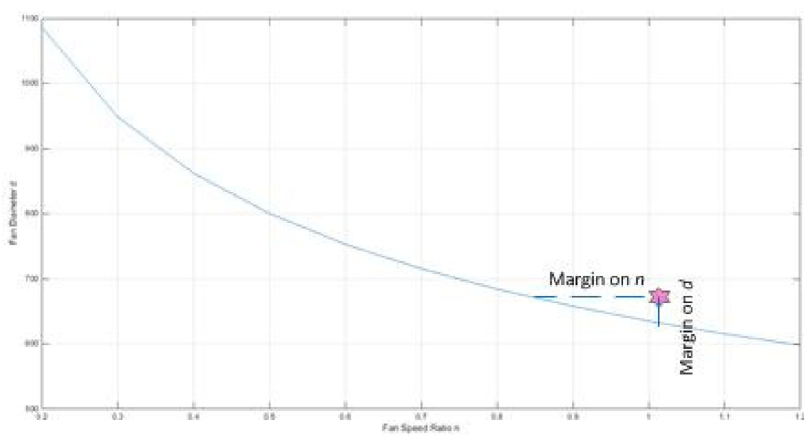

Figure 4. Different margins in different parameters

If we choose another design that give us the same flow rate, but with a design margin (18% of the air flow), it will give us another margin on *d* the fan diameter and another margin on *n* the rotational speed of the fan (Figure 5).

The mass airflow depends on the diameter of the fan and the speed with which it rotates. However both larger fans and higher rotation speed have drawback for the truck. A larger fan takes up more space and is potentially heavier, which ultimately affects engine efficiency. The fan rotation is generated by taking energy from the engine and therefore directly affects engine efficiency. Therefore the designers need to find the optimal balance between fan size and speed.

In practice the company uses only a small number of different fans, with different diameters, in an attempt to minimise the number of parts in their product platform. The fans are relatively long lead time

components. A new fan design would require the production of expensive new moulds. It would potentially also be possible to modify the geometry of the fan blades, however this would require considerable design effort from their fan supplier. The rotational speed is also not freely variable. Therefore the designer will always have a margin on the fan capacity.
The selection of the fan and the rotation speed is not only determined by the airflow, but also by other constraints. In particular as the fan is directly underneath the cab noise and noise regulations are an issue. A bigger fan would potentially generate more noise. These parameters might themselves have margins that need to be considered when making changes.

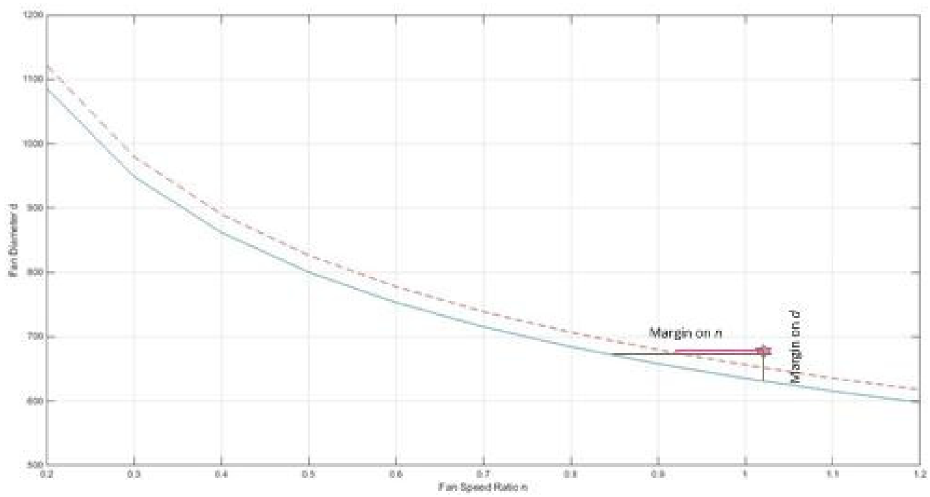

Figure 5. Relationship between margins in the design requirement and design parameters

The designers might also deliberately select a solution which has a certain margin on it, as this would give them additional room for growth in case the requirements are exceeded. Theoretically the requirements ought to be defined so that they cover these eventualities. This is the case for the particular application that they were set for. The designer however knows that another variant might have similar, but slightly higher requirements. Understanding the margins on their solutions enables the designers to reuse by adapting this solution for another application saving themselves considerable design effort.
This example illustrates how much effort designers are putting into understanding the optimal solution for each variant, even if they are constrained by the platform. One reason is that they need to be absolutely sure that the components that they have selected will be working reliably under all circumstances. In this particular problem a team of engineer works largely on design analysis. They occasionally make small changes to a component or a part of the component. However, they try to minimise these as well, as every change to a platform component requires rechecking in each combination through analysis and simulation as well as retesting the physical components.
Therefore the management or margins is also a means of managing the design effort, even at the cost that individual components or systems are overdesigned for a particular application. While there is a certain cost in terms of added fuel consumption due to increased weight is associated with an overdesigned fan, there are safety and reliability risks associated with an under-designed fan. More fans would reduce in a greater part cost and a greater design effort.

6. Conclusion

Margins play an important role at different phases of the design process. When changes occur designers can see whether the relevant margin can accommodate the change. If this is not possible, the margins on contributing parameters can guide the designers towards understanding how the change could be implemented. Margins are also a way of making explicit trade-off decisions which enables the designers to select a design solution that does not only meet the immediate needs, but also enables them to grow in the future when the next requirement change occurs. The example illustrates that margins are generally a key element in the trade-off between product and process cost. Performing a trade-off analysis using parameters that have margins allows flexibility in problem statement which does not exist in other approaches. Accepting a manageable margin can be an efficient way to manage design effort.

This is particularly important for platform products, where designers do not only consider a particular product, but also the platform as such. Each product that is built from a platform has a certain degree of margin with regards to the nearest platform component. If there is considerable cost associated with the margin, if pays the company to increase the number of components with the same functionality in the platform. For example, if a heavy metal component has a huge margin, this would seriously increase the operation cost associated with the product and it would pay the company to offer another option that is closer to the needs. This is also the reason why the company has more than one fan. For other component it does not matter if the component is overdesigned, provided the cost is not affected, leading to a trade-off between the increased cost through being overdesigned and the cost saving through communality.

Further work will look in more detail at the relationship between margins and process time as well as how analysis of margins can assist in the design of product platforms.

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